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Land Surface Temperature Measurements from EOS MODIS Data

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1. Task Objectives

1) To make beta delivery 1 of the MODIS LST (Land-Surface Temperature) product.

2) To complete version 1 of the MODIS LST ATBD (Algorithm Theoretical Base Document).

3) To update the atmospheric radiative transfer code ATRAD.

4) To develop a look-up-table based approach for retrieval of land-surface emissivity and temperature.

5) To improve the MIDAC TIR spectrometer.

2. Work Accomplished

2.1. Beta Delivery 1 of the MODIS LST Product

The MODIS LST beta delivery 1 was made to the MODIS Science Team. It is a prototype heritage software for LST from NOAA AVHRR data. Test data and basic instructions for running tests, and a brief description of the major known differences between this version of the software and the expected operational MODIS version are also included in the delivery.

2.2. The First Version of MODIS LST ATBD

The first version of the MODIS LST ATBD was submitted to Michael D. King. EOS Senior Project Scientist and the MODIS Science Team. Written comments were received from four peer reviewers during the MODIS Science Team meeting in early May. A presentation was made to the ATBD Visiting Committee on May 10, 1994. The MODIS land-surface temperature product consists of two parameters: land-surface emissivity and land-surface temperature. In the LST ATBD, land-surface temperature is proposed as an at-launch parameter, while land-surface emissivity is proposed as a post-launch parameter. For generating the at-launch 1 and-surface temperature. MODIS cloud mask, and VNIS band data will be used for clear-sky land-cover classification which is then combined with the ground-based land-surface emissivity database to assign MODIS land pixels into different emissivity groups. For MODIS pixels within each emissivity group, land-surface temperatures will be determined by MODIS TIR channel data through a specific multi-channel LST algorithm, which is derived from a statistical regression of atmospheric radiative transfer simulations in wide ranges of the atmospheric and surface renditions. Atmospheric temperature profile (Parameter No. 3726) and water vapor profile (Parameter No. 3727) will be used as additional input data for generating the post-launch land-surface emissivity from MODIS data. Rationale of this strategy is based on the current understanding of the theoretical difficulty and computational complexity in simultaneously retrieving land-surface emissivity and temperature, and the existing knowledge on emissivities of most land covers, i e., there exist relative] y stable features in the spectral emissivities of lake surface, ice/snow surface, vegetation canopy, most soil lands (referred to as A-class land-surfaces, hereafter). It was recognized that there are more variations in the emissivities of other land cover types (referred to as B-class land-surfaces, hereafter), such as bare rocks, and sands with different sizes in desert areas covered by sparse vegetations.

The major criticism from peer reviewers was focused on the strategy in the LST ATBD for the land-surface emissivity parameter. In summary, the following comments were given: (1) the effect of the uncertainty in land-surface emissivities on the at-launch LST was underestimated in the LST ATBD; (2) why are so many MODIS bands not used in the at-launch product for retrieval of land-surface emissivity and temperature? (3) land-surface emissivity should be an at-launch parameter because it is also required at-launch by other EOS products.

2.3. Update of the Atmospheric Radiative Transfer Code ATRAD

The atmospheric radiative transfer code used in the development of LST algorithms was developed by the P.I. in the early 80's, originally on PDP 11 and VAX 780 computers. Since then more and more features were added the code has been getting more flexible and complicated. Because the limitation of the main memory on general scientific computing systems in the early days, many data structures are sequentially used for multiple spectral intervals and multiple boundary conditions. In the early 80's. because the low speed of the VAX 780 it took several days to complete a moderate job. In order to get jobs done in that computational environment, the code was developed in a way such that most of the critical intermediate results, which are time consuming, could be saved on a disk. These intermediate results on the disk could be used to restart a job which was stopped due to a system crash, or used to start a new job if only boundary conditions are changed. This approach has saved a lot of computing time and increased the efficiency of the code significantly. For example, it takes only 6% of the regular computing *time* to complete radiative transfer simulations for a new boundary condition.

In 1992 the ATRAD code was ported from Sun workstations to an IBM RISC/6000 320H workstation. After some modifications including effective use of main memory for saving the first portion of the intermediate results for multiple boundary conditions, the computational efficiency is nearly doubled. The overall performance of ATRAD on the IBM workstation is 10 times faster than the performance on the original SUN 3/60 workstation. Therefore, multiple scattering radiative transfer simulations could be made at a higher spectral resolution and with more molecular absorption terms.

A new DEC Alpha 3000 model 800 workstation was purchased in the second quarter of this year. It has a total main memory of 192Mb. After the ATRAD code was ported to the new 64-bit workstation, its program and data structures have been cleaned and modified so that sequential processing for multiple boundary conditions is performed in an array structure form in the main memory. The new data structures also make it easy to change the code for parallel radiative transfer simulations over multiple spectral intervals on parallel computing systems. For the modified ATRAD rode, the speed on the new Alpha workstation is about 2.8 times of the speed on the IBM RXSC/6000 320H workstation.

2.4. The Development of A New Approach - Look-Up-Table Method

2.4.1. Background

After the ATBD Review Meeting in early May, immediate consideration was given to the comments summarized previously. A reasonable and positive response to these comments is to change the land-surface emissivity into an at-launch parameter. This means that the whole development schedule for the MODIS LST algorithm has to be accelerated for about one or two years. Another important thing to consider is. that the computational requirements for the LST production at-launch should not be increased significant y (a factor of 2 may be still reasonable). Because of the coupling between the Earth's atmosphere and surface, more MODIS TIR bands should be used to simultaneous y retrieve land-surface emissivity and temperature, and atmospheric temperature and water vapor profiles. A comparative analysis of the MODIS bands with the channels of the NOAA High resolution Infrared Radiation Sounder (HIRS-2) [1] shows that MODIS has 10 bands (bands 27 to 36) in the wavelength range 6-15 µm, and 6 bands (bands 20 to 25) in the range 3-5 pm. Among these MODIS bands, four 15µm band channels and two 4.3 µm band channels could be used for atmospheric temperature sounding, and 2 or 3 more channels could be used for water vapor sounding, as shown in Table 1. If we constrain ourselves to the longer wavelength range 6-15µm in the first stage so that we do not have to make corrections for the solar radiation effect in the range 3-5 µm, it is possible to use 8-10 MODIS bands for retrieval of land-surface temperature and band-averaged emissivities, atmospheric temperatures at 4-5 levels (up to about 9km from the surface) and water vapor values at 2-3 levels in the lower atmosphere. More MODIS bands could be used for the retrieval purpose at night. In theory, it is possible to retrieve atmospheric and land-surface parameters with a pair of daytime and nighttime MODIS data sets without any empirical knowledge of the surface emissivity if we can assume that there is no diurnal variation in the surface emissivity. But this assumption may be questionable for the B-class land-surface due to the possible dew effect on the surface emissivity at night. Therefore, some minimal empirical knowledge of spectral features and relations in the band-averaged land-surface emissivity is still required. especially in and near the atmospheric windows where surface emissivity has stronger effects on the TIR radiance at the top of the atmosphere. In order to achieve the 1°K requirement for LST, an accurate radiative transfer model should be used to relate MODIS TIR band radiance values to the atmospheric and surface conditions. Again, because of the coupling between the Earth's atmosphere and surface, iterations are required in the retrieval processing.

The accurate and computationally effective approach for at-launch operational production will be to use look-up tables that give TIR band values at discrete values of the land-surface temperature and emissivity, and at discrete values of the atmospheric temperature and water vapor. In order to assure the retrieval accuracy and to limit the computational requirement to a reasonable level, it is proposed that the full retrieval processing be conducted at a small regional level, say, for relative uniform or uniformly mixed B-class land-surfaces covered by 5 by 5 MODIS lkm-resolution pixels. The reasons behind this decision are as follows: 1) For most MODIS TIR bands, the noise equivalent temperature difference (NEAT) is specified as 0.25°K and the absolute radiometric accuracy requirement is specified as 1% (compared to 0.05°K and 0.5%, restively, for bands 20, 31 and 32 designed for surface temperature). Therefore an average over 25 pixels is necessary to increase the signal-to-noise ratio of the TIR data 2) The accuracy of the full retrieval will be affected by variations and uncertainties in boundary areas. This kind of uncertainty should be avoided. For pixels in boundary areas, a simpler and less accurate method will be used to estimate the surface emissivity by a combined use of NDVI and VNIR data and interpolating the emissivity values of neighbor pixels from the full retrieval, and then to estimate the surface temperature by the multi-channel LST algorithm. 3) It is not really necessary to routinely spend much computer time on the full retrieval processing routinely for A-class land-surface pixels if we can easily estimate the emissivity group of these pixels by using MODIS VNIR data simple land-cover classifications, and NDVI, and then use much simpler multi-channel LST algorithms to retrieve the land-surface temperature at the pixel level. The full retrieval processing, however, will be performed at some selected A-class land-surface sites for the purpose of checking the internal consistency of the MODIS LST product.

In terms of the relation between the MODIS LST product and the atmospheric temperature profile (Parameter No. 3726) and water vapor profile (Parameter No. 3727), the later could be used as initial conditions of the atmospheric parameters in the LST full retrieval processing. The MODIS LST full retrieval processing will provide atmospheric temperature and water vapor profiles at only a limited number of land-surface sites.

In the following sections, some preliminary feasibility analysis of the look-up-table approach will be presented in terms of showing the effects on the TIR radiance at the top of the atmosphere of the stratospheric and upper atmospheric temperature profiles, the surface emissivity and temperature, the lower atmospheric temperature and water vapor profiles, and the viewing angle. The TIR radiance at viewing zenith angles up to 64° from vertical is given by the accurate radiative transfer model ATRAD which includes atmospheric molecular and aerosol absorption/emission, and multiple scattering of aerosols. The standard atmospheric models used in the AFGL MODTRAN code, including tropical. mid-latitude summer and winter, subarctic summer and winter, and a 30-year averaged summer atmospheric profile of South Japan (latitude < 30°N, Courtesy of T. Ariyama, personal communication), were used in radiative transfer simulations. The temperature and relative humidity profiles are shown in Figures 1 and 2. respectively.

2.4.2. The effect of stratospheric and upper atmospheric temperature profiles

We made radiative transfer simulations for the tropical atmosphere, and a synthetic atmospheric profile which comes from replacing the stratospheric and upper atmospheric temperature and water vapor profiles of the tropical atmosphere with the summer subarctic atmosphere (i.e., the temperature and relative humidity profiles above 9km elevation were changed). It was found that the effect of changing the temperature profile above 9km elevation on the radiance values for MODIS bands 31 and 32 is small enough (0.02% and 0.1 % at zenith angle 00 and 640, respective] y). Because the longest wavelength covered by MODIS band 36 is about 14.4μm, MODIS TIR bands are not sensitive to the temperature profile in the stratospheric and upper atmospheric ranges. The simulation results show that this is not a problem for land-surface emissivity and temperature retrieval.

2.4.3. The effects of surface emissivity and temperature

The thermal infrared spectral signature measured from satellite-borne sensors maybe expressed [2] as

$$
\begin{aligned}
L(j) = {} & t_1(j)\,\varepsilon(j)\,B(j, T_s) + \\
& \pi^{-1}\,[1-\varepsilon(j)]\,[t_2(j)\,E_a(j) + t_3(j)\,E_s(j)] + \\
& L_a(j) + L_s(j)\,. \qquad (1)
\end{aligned}
$$

The factors *ti(j), i* = 1,2,3 are three effective transmission coefficients for band *j:* for surface thermal emittance, atmospheric downward thermal irradiance reflected by the surface, and solar irradiance reflected by the surface, L_a is the atmospheric upward thermal radiance, and L_s is path radiance resulting from scattering of solar radiation. Note that the solar radiation terms E_s and L_s in the equation could be neglected for MODIS bands 27 to 36 at any time and for any MODIS bands at night.

Because equation (1) is linear in E(j) and B(j, T_s), it is possible for a look-up table to just keep 4 band radiance values at two surface emissivity values (say 0.5 and 1.0) and two surface temperature values, which are wide enough to cover the whole range of the surface emissivity and temperature variations. Then, radiance values for any surface emissivity and temperature values could be derived from this look-up table by using linear interpolations. By comparing simulation results with values interpolated from the look-up table, it is shown that the accuracy of the linear interpolation is better than $3x10^{-5}$ for the surface emissivity and better than $1x10^{-5}$ for B(j, T_s).

2.4.4. The angular dependence of TIR radiances at the top of the atmosphere

The next problem is how many zenith angles are necessary to be kept in the look-up table for TIR radiance at the top of the atmosphere. The maximum scan angle of the MODIS instrument is ±55° from nadir, this gives maximum viewing zenith angle ±65° on the horizontal ground surface due to the curvature of the Earth. So we need to accurately know TIR radiance values in the viewing zenith angle range from 0 to 65°. We made two radiative transfer simulations for the same tropical atmosphere and same surface conditions, one giving radiance values at 16 zenith angles (including 8 angles in the upwelling direction) and another giving radiance values at 24 zenith angles. The angular dependence of the band averaged radiance values for MODIS bands 31 and 32 are shown in Figure 3. We can see that the band radiance will lie on a single line if these points are connected by stepwise quadratic interpolations. To test this approximation, the radiance values at the top of the atmosphere from the 16-stream simulation at 4 zenith angles (1 1.4°,40.3°, 53.7°, and 65.9°, respectively) are put in a look-up table. Then, a 3-point interpolation is used to get radiance values at the quadratic angles used in the 24-stream simulation in the 0° to 65° range. These values are compared to the band average radiance values derived directly from the 24-stream simulation results. The difference is less than 0.055% for MODIS bands 31 and 32. This excellent agreement between these two sets of results indicates that 16-stream simulations are accurate enough for the development of LST algorithms, and that the 3-point interpolation is appropriate.

2.4.5. Variation of TIR radiances with atmospheric column water vapor

As is well known, the atmospheric water vapor has the strongest effect on the TIR signature measured by satellite sensors in the atmospheric windows, and the atmospheric water vapor also highly varies with time and location. In order to simulate its high variation we scale the tropical water vapor profile by a factor from 0.05 to 1.25 (corresponding to water vapor changes from a very dry condition to a very wet condition where the relative humidity near surface is close to 100%). Similar scalings were made to water vapor profiles of south Japan summer, mid-latitude summer and winter, subarctic summer and winter. The dependence of atmospheric transmission functions on column water vapor for MODIS bands 31 and 32 are shown in Figure 4 for all of these atmospheric conditions. It should be pointed out that the band-averaged transmission is not an exponential function of the column water vapor, which is often applied by researchers to approximate the band-averaged atmospheric transmission. The exponential transmission approximation does not apply because there are many weak absorption lines even in a narrow band in the atmospheric windows. It is also shown in Figure 4 that the atmospheric temperature profile has a significant effect on the atmospheric transmission, although it is dominated by the water vapor effect The band ratio of the transmission functions for MODIS band 32 to band 31 is shown in Figure 5. Again, it is not an exponential function of the column water vapor in the whole range, although it could be approximated by an exponential function in a limited range.

A regression analysis shows that this band ratio maybe expressed as

$$\frac{t_{32}}{t_{31}} = \frac{1}{1 + 0.0146\,(w + 0.595)^2} \tag{2}$$

where w is column water vapor in g/cm^2. The standard deviation (0.02) and the maximum deviation (0.07) have to be taken into serious consideration in the development of LST algorithms with a goal of 1°K accuracy. If the increment of the column water vapor in a look-up table is 25%, the radiance error given by the 3-point interpolation is 0.1% in the zenith angle range 0° to 65° for MODIS bands 31 and 32. This corresponds to a AT about 0.07°K, slightly larger than the specification of NEAT (noise-equivalent temperature difference).

2.4.6. Perspective of the look-up table approach

So far, all the preliminary investigations are very promising for the look-up table approach. The next critical step is to simulate the effect on TIR radiance of changing the atmospheric temperature profile over a wide range and to determine how to build the look-up tables to accurately describe this effect for all MODIS TIR bands.

The estimated size of the look-up table for a seasonal climatic zone is about 150-250Mb. It is assumed that four bytes will be used for storing one band radiance value. If two bytes are used for storing one radiance value in form of binary fraction, it is need to be converted to real number with its physical unit during each step of the retrieval processing for land-surface emissivity and temperature, and atmospheric temperature and water vapor profiles. The accuracy requirement for the look-up table approach and corresponding interpolation methods is set to 0.1 %. Then the above estimated size was derived from the following parameters (atmospheric temperature to be retrieved at 4 level, *8* different values for the temperature at each level, atmospheric water vapor to be retrieved at 2 level, 8 different values for the water vapor at each level, 2 emissivity values and 2 temperature values for the land-surface, band radiance values at 4 zenith angles to be stored, 10-15 MODIS bands to be included) based on the analysis results in the above sections. The look-up table size will be much larger if the solar effect on the azimuth distribution of TIR radiance is included.

2.5. Improvement of the TIR Spectrometer

Based on test results of the MIDAC TIR spectrometer in the last year, investigations have been made to improve the performance of the spectrometer. First of all, the spectrometer should be stablized by cooling the beamsplitter unit, one of its critical components, to a fixed temperature slightly lower than the environment temperature with a controlled thermoelectric cooler. With this cooling, the system response function will be stablized, and the SNR in the medium wavelength range 3.5-4.3 micron will be improved. It was found that the original InSb/MCT sandwich detector which MIDAC Corp. ordered from Graseby Infrared for the spectrometer had poor SNR in the medium wavelength range at low temperatures, and exhibited the channeling effect in the output signal because of multiple reflection between two detector elements. Graseby Infrared could not solve these two problems in the past several months. I contacted several companies which build TIR detectors. Only EG&G Judson promises to eliminate the channeling effect by wedging the detector surface and to build a sandwich detector which performs better than an MCT detector in the wavelength range 3-15 micron. So I urged MIDAC Corp. to order a LN2-cooled InSb/MCT sandwich detector from EG&G Judson for the TIR spectrometer. The detector size is specified as 1 by 1 mm, and the cold stop as 40°. in order to achieve a better SNR. It is expected that this detector will be received in July.

A pointing structure has been designed and is under construction. It will be used for measurements of 1 and-surface emissivity/temperature at a variable viewing angle over almost the whole hemisphere,

3. Anticipated Future Actions

l) to prepare the beta delivery of the LST algorithm in October;

2) to continue the work for development of the look-up table approach which will be used for simultaneously retrieval of land-surface emissivity and temperature from MODIS data;

3) to make emissivity and temperature measurements of water surface and grass field with the MIDAC M2401 spectrometer;

4) to participate in the SCAR-C experiment and make field measurements with the TIR spectrometer in September.

4. Publications

1. J. Dozier and Z. Wan, "Development of practical multiband algorithms for estimating land-surface temperature from EOS/MODIS data", Advances in Space Research, Vol. 14, No. 3, pp. 81-90, 1994.

2. Z. Wan, D. Ng and J. Dozier, "Spectral emissivity measurements of land-surface materials and related radiative transfer simulations", Advances in Space Research, Vol. 14, No. 3, pp. 91-94, 1994.

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[1] W. L. Smith, H. M. Woolf, C. M. Hayden, D. Q. Wark, and L. M. McMillin, "The TIROS-N operational vertical soundr," *Bulletin American Meteorological Society,* vol. 60, no. 10, pp. 1177-1187, 1979.

[2] Z. Wan and J. Dozier, "Effects of the atmosphere and surface emissivity on the thermal infrared spectral signature measured from MODIS-N," *Proceedings IGARSS '90,* pp. 189-192, 1990.

TABLE 1. Correspondence between MODIS TIR bands and TOV sounding channels.

MODIS band number	MODIS bandwidth (µm)	HIRS channel number	center wavelength (µm)	principal absorbing constituents	level of peak energy contribution	purpose of the radiance observation
		1	15.00	CO_2	30mb	temperature sounding
		2	14.70	CO_2	60mb	temperature sounding
		3	14.50	CO_2	100mb	temperature sounding
36	14.085-14.385	4	14.20	CO_2	400mb	temperature sounding
35	13.785-14.085	5	14.00	CO_2	600mb	temperature sounding
34	13.485-13.785	6	13.70	CO_2/H_2O	800mb	temperature sounding
33	13.185-13.485	7	13.40	CO_2/H_2O	900mb	temperature sounding
32	11.770-12.270					surface temperature
31	10.780-11.280	8	11.10	window	surface	surface temperature
30	9.580-9.880	9	9.70	03	25mb	total ozone
29	8.400-8.700	10	8.30	H_2O	900mb	water vapor/surf. temp.
28	7.175-7.475	11	7.30	H_2O	700mb	water vapor
27	6.535-6.695	12	6.70	H_2O	500mb	water vapor
		13	4.57	N_2O	1000mb	temperature sounding
25	4.482-4.549	14	4.52	N_2O	950mb	temperature sounding
24	4.433-4.498	15	4.46	CO_2/N_2O	700mb	temperature sounding
		16	4.40	CO_2/N_2O	400mb	temperature sounding
		17	4.24	CO_2	5mb	temperature sounding
23	4,020-4.080	18	4.00	window	surface	surface temperature
22	3.929-3.989					surface temperature
20	3.660-3.840	19	3.70	window	surface	surface temperature

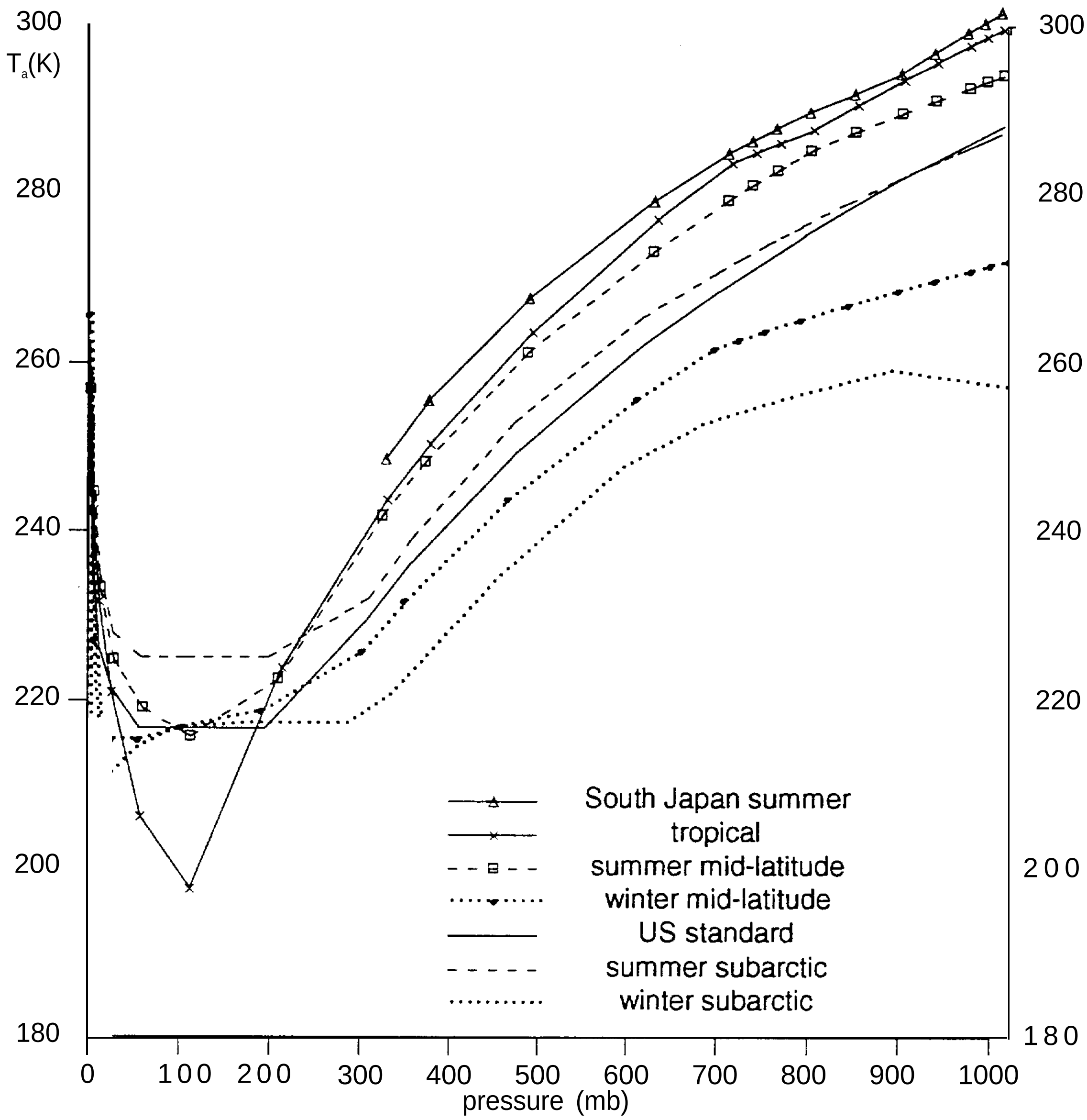

Figure 1. Atmospheric temperature profiles used in simulations.

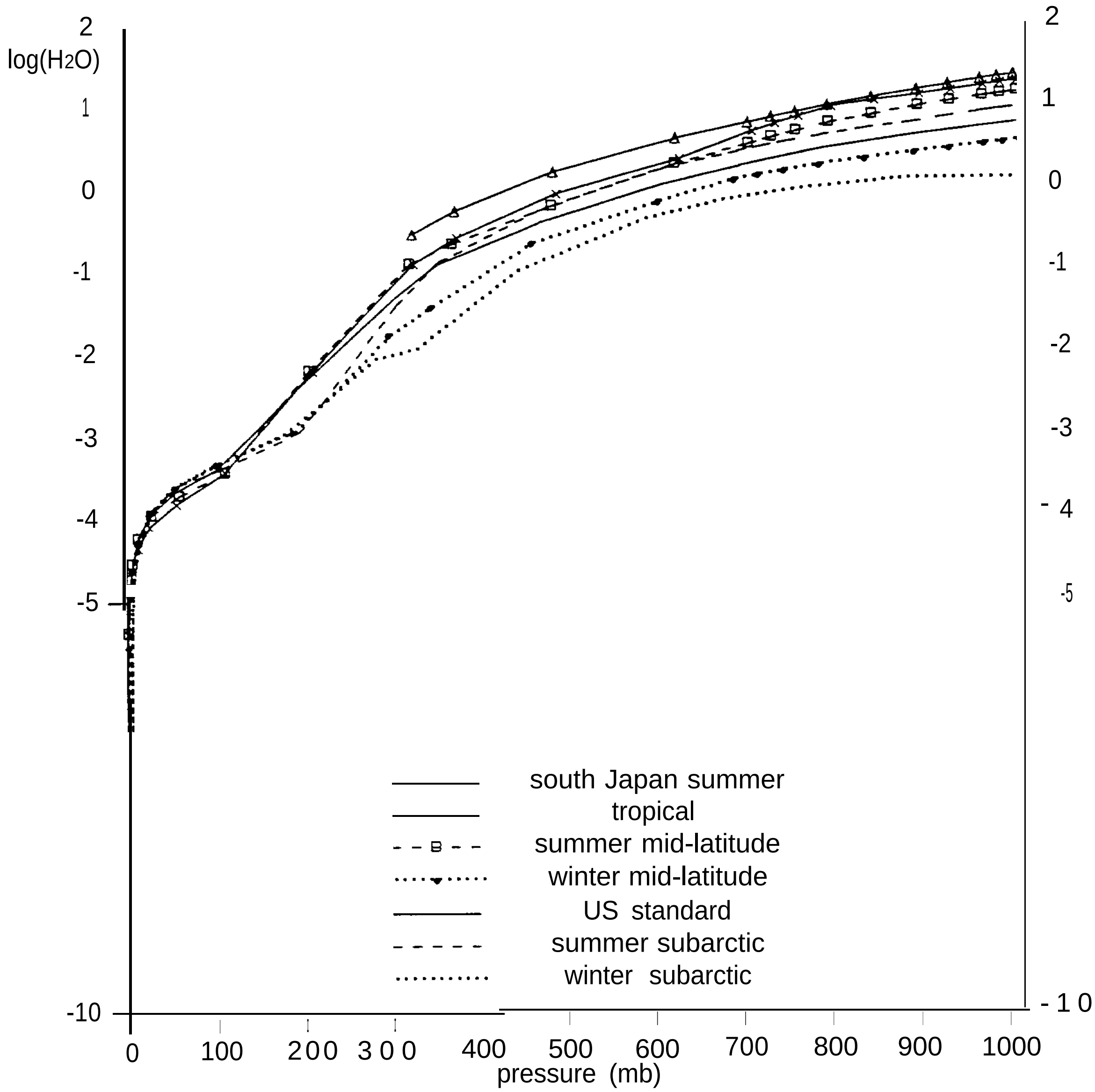

Figure 2. Atmospheric water vapor (gm^{-3}) profiles used in RT simulations.

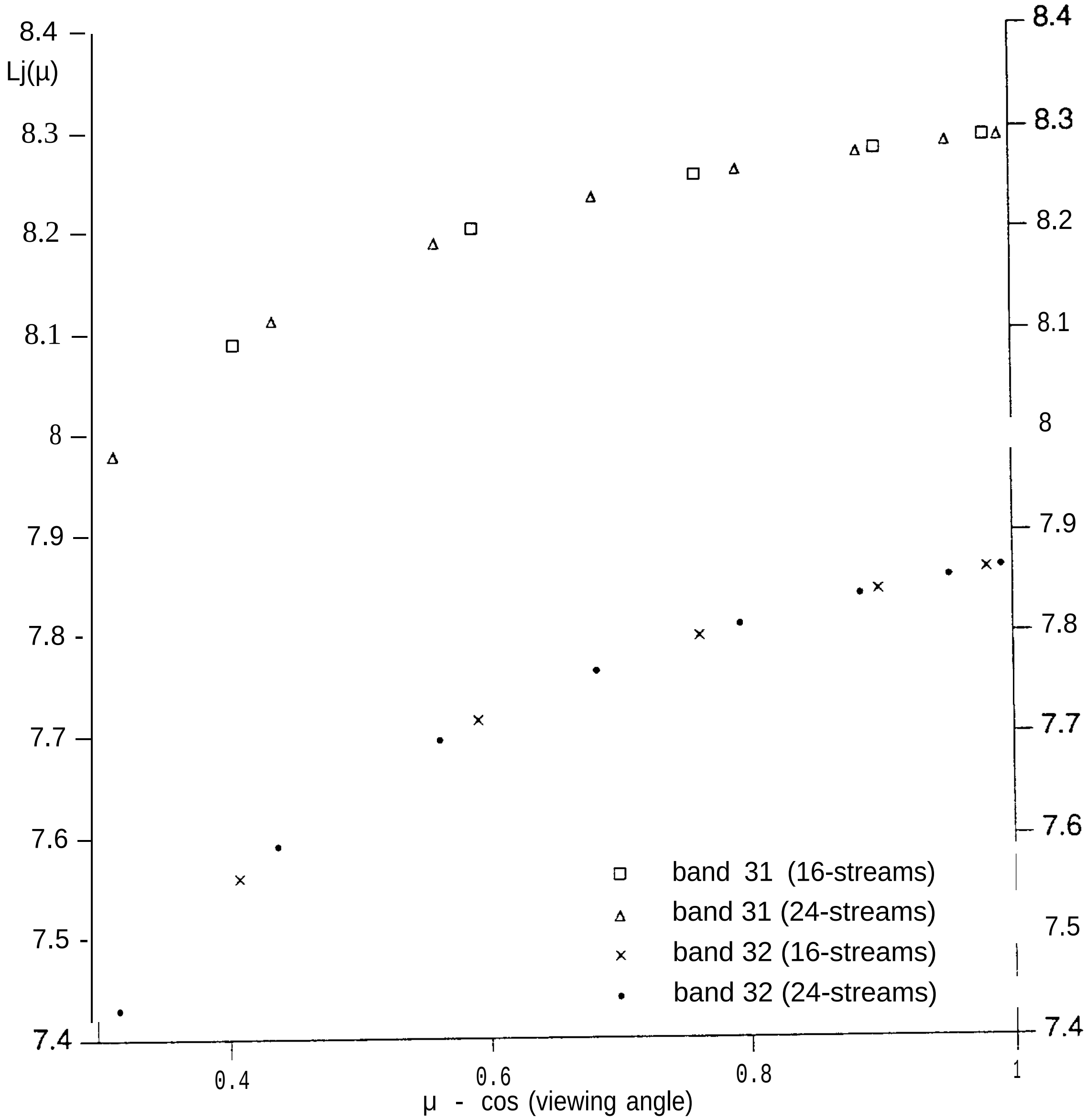

Figure 3. The angular dependence of of TIR radiances at the top of the atmosphere.

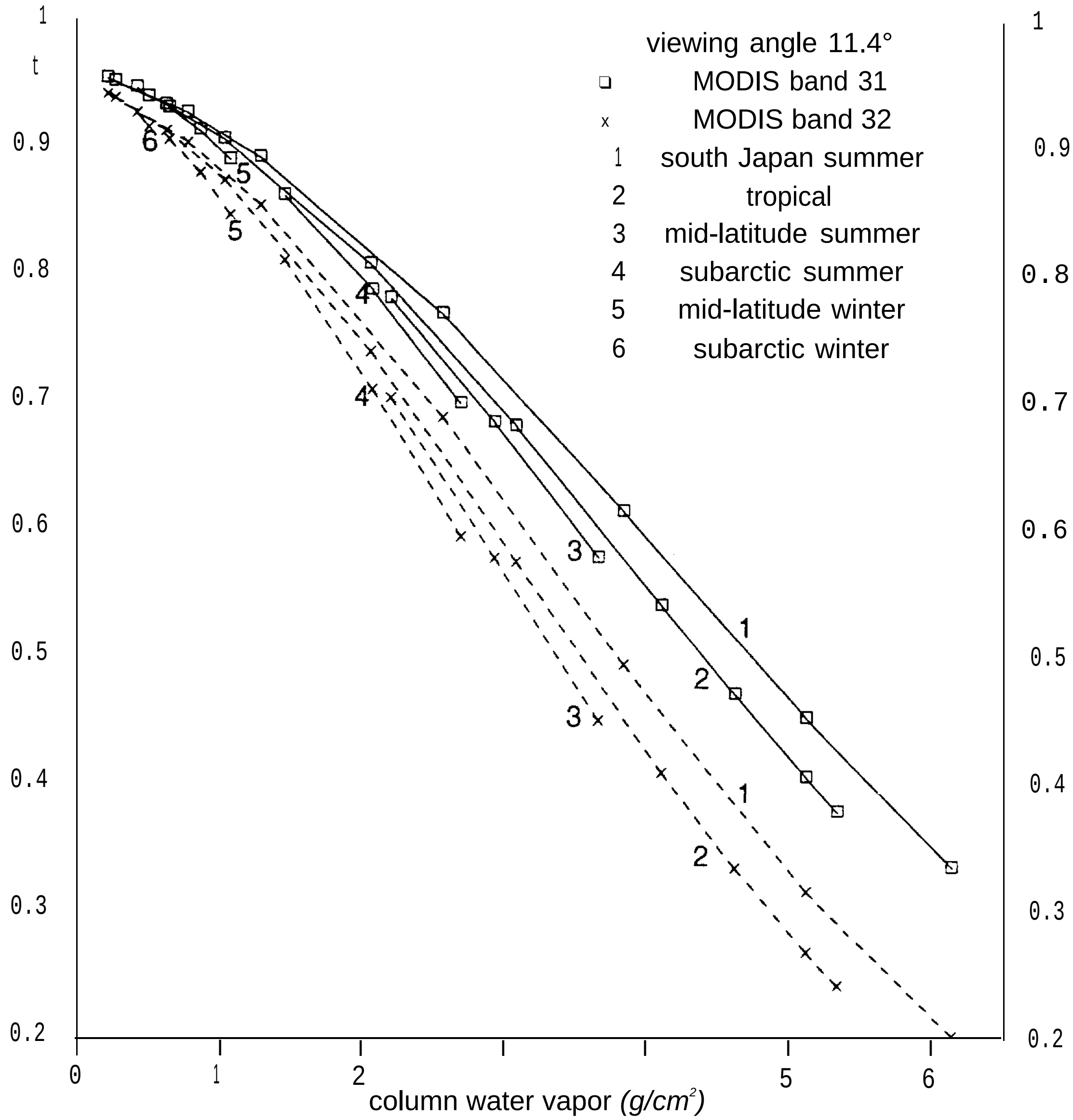

Figure 4. Dependence of atmospheric transmission on atmospheric water vapor and temperature,

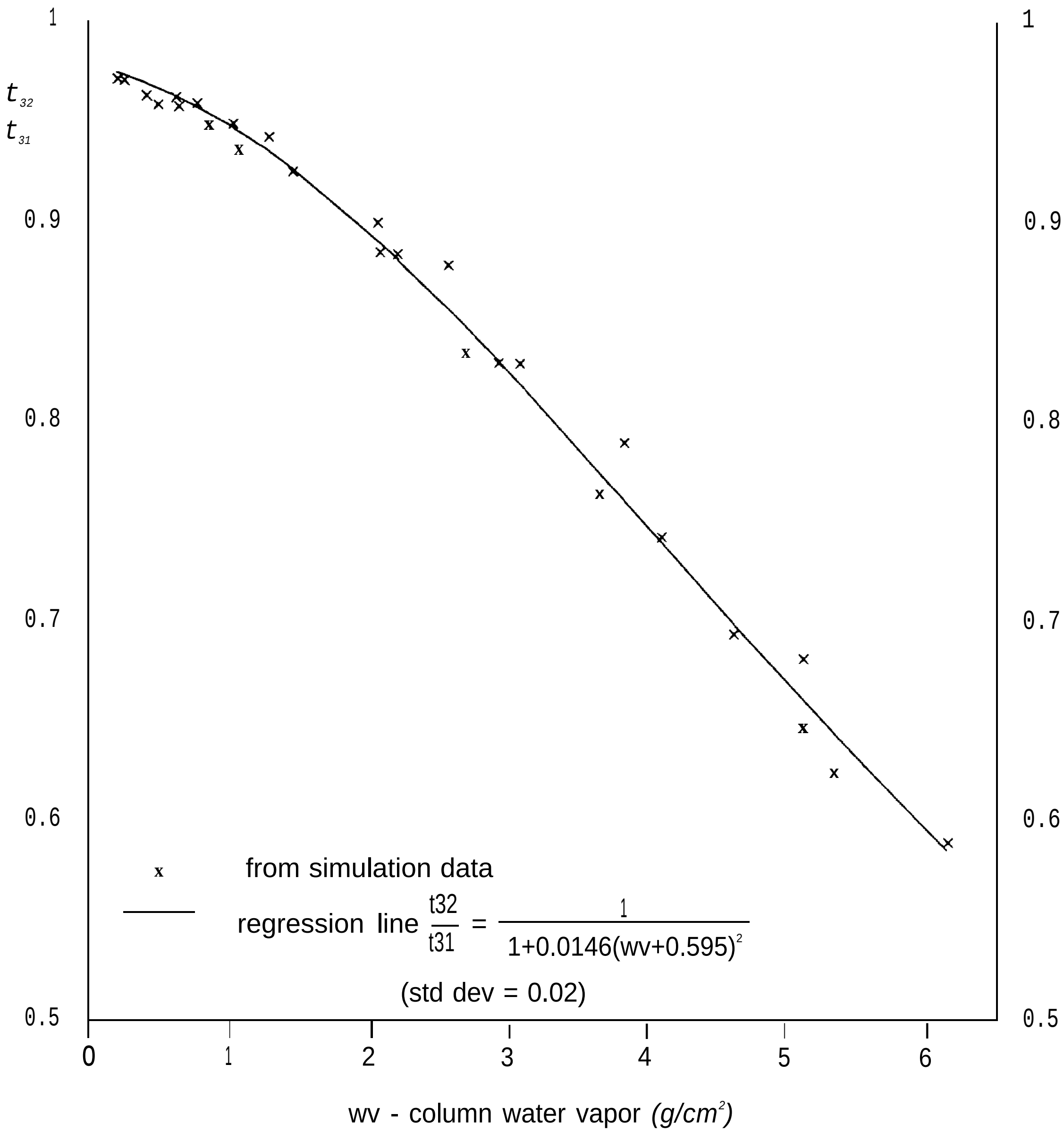

Figure 5. Ratio of band atmospheric transmissions versus column water vapor.